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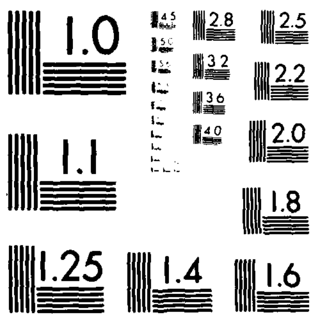

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STRESS FIELD EFFECTS ON DYNAMIC FRACTURE

FINAL REPORT

I. M. FYFE

DECEMBER 1981

U. S. ARMY RESEARCH OFFICE

GRANT DAAG29-77-G-0211
GRANT DAAG29-80-C-0128

DEPARTMENT OF AERONAUTICS AND ASTRONAUTICS
UNIVERSITY OF WASHINGTON
SEATTLE, WASHINGTON

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SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER DAAG29-77-G-0211	2. GOVT ACCESSION NO.
3. RECIPIENT'S CATALOG NUMBER	
4. TITLE (and Subtitle) STRESS FIELD EFFECTS ON DYNAMIC FRACTURE	5. TYPE OF REPORT & PERIOD COVERED FINAL, Sept. 1977 - Oct. 1981
	6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Ian M. Fyfe	8. CONTRACT OR GRANT NUMBER(s) DAAG29-77-G-0211 DAAG29-80-C-0128
9. PERFORMING ORGANIZATION NAME AND ADDRESS Department of Aeronautics and Astronautics University of Washington Seattle, WA 98195	10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS U. S. Army Research Office P. O. Box 12211 Research Triangle Park, N.C. 27709	12. REPORT DATE December, 1981
	13. NUMBER OF PAGES
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office) N.A.	15. SECURITY CLASS. (of this report) Unclassified
	15a. DECLASSIFICATION/DOWNGRADING SCHEDULE N.A.

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

N.A.

18. SUPPLEMENTARY NOTES

The findings of this report are not to be construed as an official Department of the Army position, unless so designated by other authorized documents.

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Dynamic Fracture
Fracture Mechanics
Spallation
Ductile Fract
Failure Criteria

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

The introduction of inertia terms in the theoretical model of thin ring expansion showed that the classical plastic instability concepts, defined in terms of the local strain in the necking region, no longer applied. The introduction of the role of void growth in triggering local necking, through the recently proposed constitutive equation for porous plastic materials allowed this difficulty to be overcome.

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A criterion based on a critical void volume fraction provided the alternative means to predict failure. This theory was applied to number of configurations (thin ring, thick plate and thick cylinder) under high strain rate loading conditions, and the theoretical results were found to compare favorably with experimental values.

Problem Statement

The basic objective of this research project was to examine dynamic fracture criteria to determine if the material constants of the failure process can be obtained by using a relatively simple experimental configuration; with the requirement that the dynamic failure process can be predicted with sufficient generality, to allow its application to impact conditions with various geometries and stress fields.

Study Sequence

To achieve the above objectives the study was conducted in essentially five phases. Each phase was undertaken to examine a specific aspect of the failure process, and each one was a logical extension of the one before. This study sequence can be summarized as follows:

(1) Existing failure criteria were examined to determine their ability to predict failure under different impact conditions and geometries.

(2) A combined theoretical and experimental study was undertaken to determine a failure model appropriate to the prediction of static and dynamic failure in thin rings and cylinders.

(3) The model developed in (2) was applied to the prediction of failure in thick plates, as represented by the uniaxial strain plate impact experiments.

(4) An improved failure model was introduced which incorporated continuous void nucleation into the model developed in (2).

(5) Improved experimental techniques were developed for thin ring failure analysis, to allow the failure properties of high strength steels to be determined.

Results

The main results obtained during the course of the study can be summarized in terms of each phase, and these were as follows:

(1) It had been the intention to use one of two existing dynamic failure criteria, and adapt them for application to the thin ring configuration. It was determined that neither the accumulative damage model of the form:

$$\int_{t_1}^{t_2} (\sigma-\sigma_0)^{\lambda} dt = K \qquad \sigma > \sigma_0$$

or the void growth model

$$\frac{R}{R_0} = \exp \int_0^t \frac{\sigma - \sigma_{g0}}{4\eta}\, dt, \qquad \frac{\dot{N}}{\dot{N}_0} = \exp \frac{\sigma - \sigma_{n0}}{\sigma_0}$$

could be used in both the plate impact and ring configurations, mainly because the material constants (σ_0, λ etc.) appropriate to one configuration did not apply to the other.

Further, it was found that the quasi-static void growth model of Rice and Tracey [2] did not give consistent results when applied to situations where high strain-rate conditions prevailed. However, as this model was not developed for dynamic problems these results were not too surprising.

(2) Recent developments in the use of long wave-length plastic stability criteria, as outlined by Hutchinson and Neale [3], together with the use of the Gurson yield function [4], suggested an entirely different approach to the problem of dynamic ductile failure. This yield function has the form

$$\phi = \frac{3J_2}{Y_m^2} + 2\, f \cdot \cosh\left(\frac{\sigma_{kk}}{2Y_m}\right) - f^2 - 1 = 0 \qquad \text{(a)}$$

where f is the void volume fraction, and Y_m is the flow stress of the matrix material. The compressibility of the plastic material is introduced through the relation

$$\dot{f} = (1 - f)\ (\dot{\varepsilon}_1{}^p + \dot{\varepsilon}_2{}^p + \dot{\varepsilon}_3{}^p) \qquad \text{(b)}$$

The theory appropriate to the study of the static and dynamic failure of thin rings was developed, together with a companion set of experiments. This approach gave very encouraging results, as shown in Fig. 1. The material property associated with failure, the critical void volume fraction, was obtained. It was also noted that the dynamic results were not particularly sensitive to the strain-rate sensitivity of the material. Details of this work have been reported in [5], [6], and [7].

(3) The above theory when applied to a computer program which had been previously developed to analyze the spallation process associated with plate impact, produced the results shown in Fig. 2. The predicted spall threshold obtained, using the ring-generated critical void volume fraction, was not unreasonable, but certainly higher than one would expect of a model that did not include void coalescence. The scatter in the experimental data, due mainly to the different methods used to define spallation posed a problem. It was felt that the Sandia data presented by Butcher and Young [8] not only reflected a consistent definition of incipient spallation, but also was presented with sufficient detail that it should be used as a reference for the theories developed in this project. When the calculated value of the peak normal stress threshold are compared with the Sandia values the correlation is much better, as shown in Fig. 3. The better agreement obtained in this latter case is an indication of the importance of strain-rate sensitivity in the constitutive model. Another shortcoming of the model is that it does not reflect the increased threshold that occurs as the pulse duration is shortened.

(4) The above model assumes that all the void nucleation occurs at the onset of yielding. Realistically one would expect that nucleation would occur during the plastic deformation, and depend on the history of that deformation. The model was changed to include continuous void nucleation by altering equation (b) as follows:

$$\dot{f} = (1 - f)\ (\dot{\varepsilon}_1^{\,p} + \dot{\varepsilon}_2^{\,p} + \dot{\varepsilon}_3^{\,p}\ ) + F \cdot \dot{\varepsilon}^p$$

where F is a distribution function that depends on the history of the plastic strain. The constants appropriate to F were obtained from the history of the effective plastic strain. The Sandia experiment which produced spallation at the lowest stress value was used in this case (i.e. experiment 4 in Fig. 4). The results obtained from this improved model are shown in Fig. 3 and 5, and the hoped-for change seems to have been obtained. To get some idea of the generality of this model it was then applied to spallation in a dynamically loaded thick-walled cylinder, and the results are shown in Fig. 6. In this case the results were very good for one pulse, but slightly out in the case of a very short high intensity pulse. However, it is possible that the loading pulse was not as precisely defined in the latter case. Although F was chosen to be compatible with the righ configuration the ring programs have not as yet been altered to reflect the change.

(5) The complexities associated with determining material properties under dynamic loading almost excludes the possibility of relying on one experimental configuration in this type of work. In the case of failure properties the results of this study indicate the ring configuration can provide valuable data. The experimental techniques used in this study, as described in [5], although ideally suited to some materials, may not provide either the high strain-rates or the

loading levels required to make this technique applicable to high strength materials. The relative simplicity of an exploding-wire system, and the fact that the loading pressures are not required allowed the system to be adapted to meet these additional requirements, and the configuration shown in Fig. 7 was developed. The appropriate shape of the water filled cavity (not shown in Fig. 7) required to produce the appropriate uniaxial hoop expansion is the key to this system. This technique was developed to the point of showing its feasibility, but no attempt has yet been made to obtain fracture data.

Computer Programs

The following computer programs were used in the analysis related to this project:

(1) "VOIDS" : - a Runge-Kutta solution of the quasi-statically deformed thin ring; used to obtain the critical void volume fraction.

(2) "DYNVOID" : - similar to "VOIDS" except that it includes inertia terms required in the analysis of impact loaded thin rings.

(3) "HOSLAP" : - a method of characteristic solution which determines the stresses, displacements, strain and void growth levels resulting from plate impact.

(4) "CYCLOPS" : - a cylindrical version of "HOSLAP" which determines the response of a thick-walled cylinder to an internal pressure pulse.

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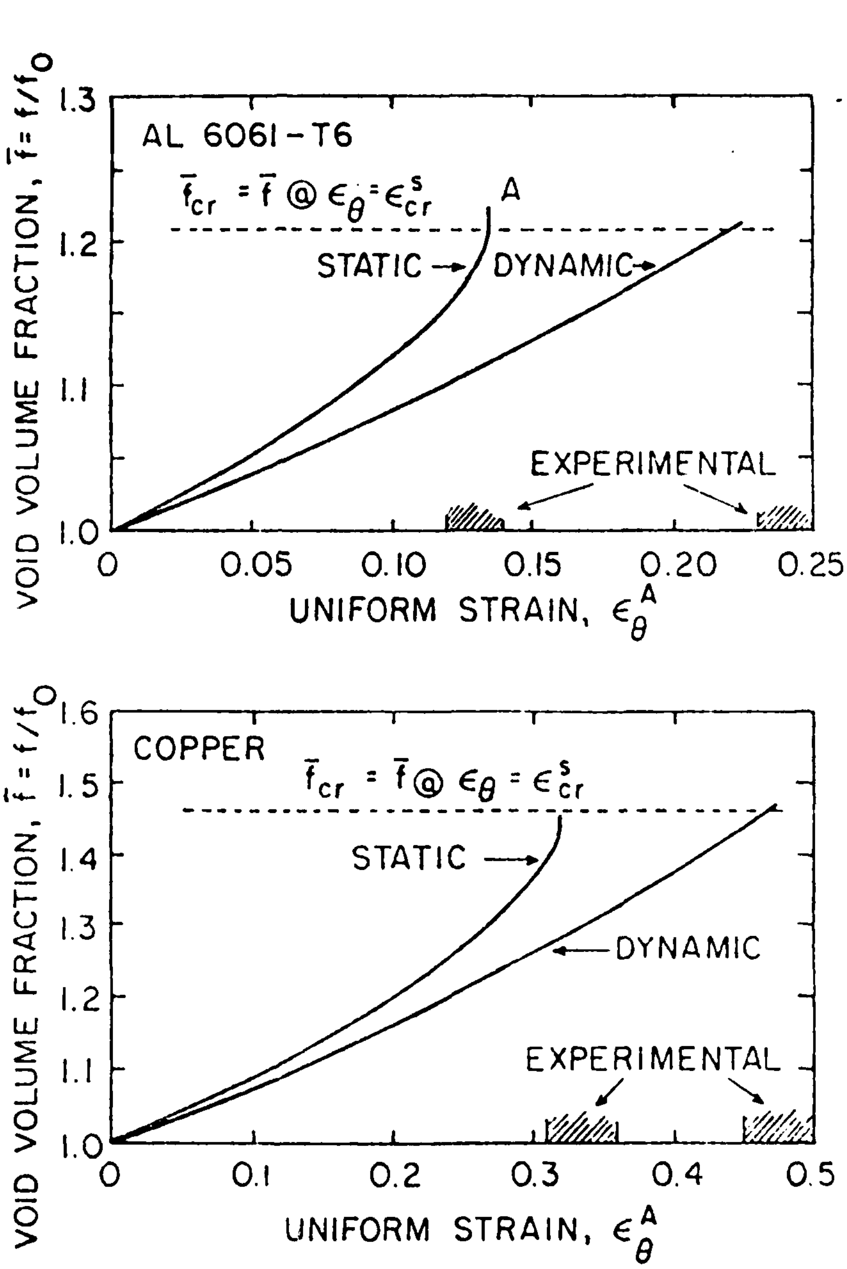

Fig. 1 Critical Void Volume Criterion Applied to Thin Rings of Aluminum and Copper. ($\eta = 0.03$, $\Delta f = 0.01$, $\dot{\varepsilon}_0 = 8 \times 10^3$/sec).

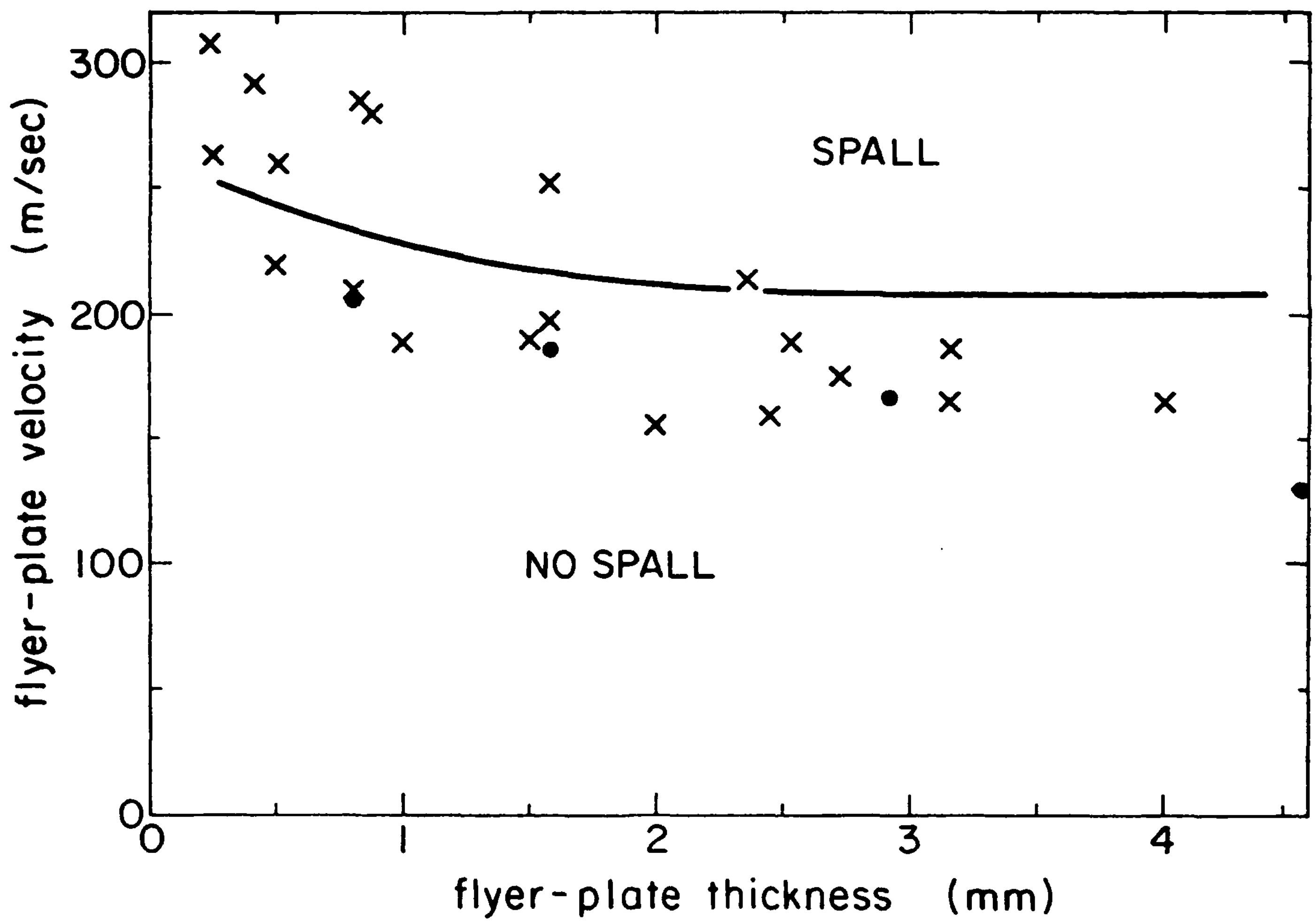

Fig. 2 Spallation Threshold for Aluminum 6061-T6
(x - general experimental values, ● - Sandia data, ref. 8,
—— simple void growth theory)

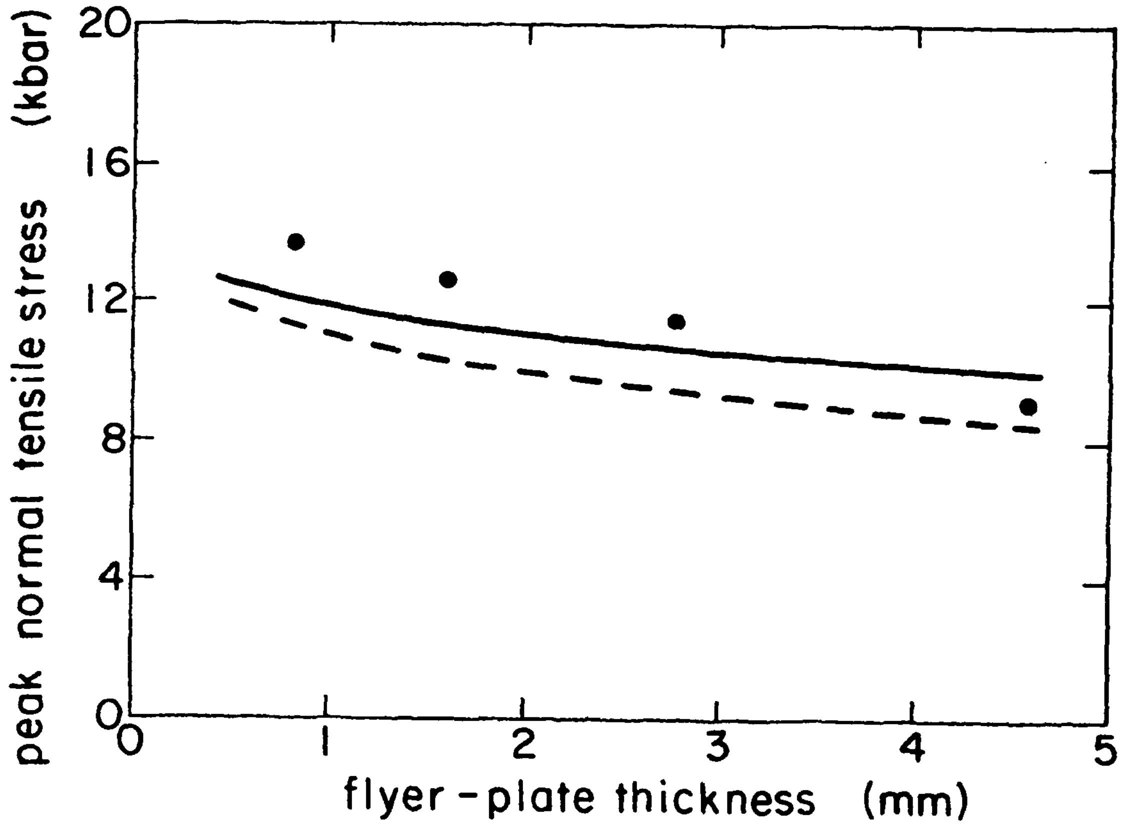

Fig. 3 Normal Tensile Stress at Incipient Spall.
(● Sandia experimental data, ref. 8;
—— simple void growth model;
---- nucleation/void growth model)

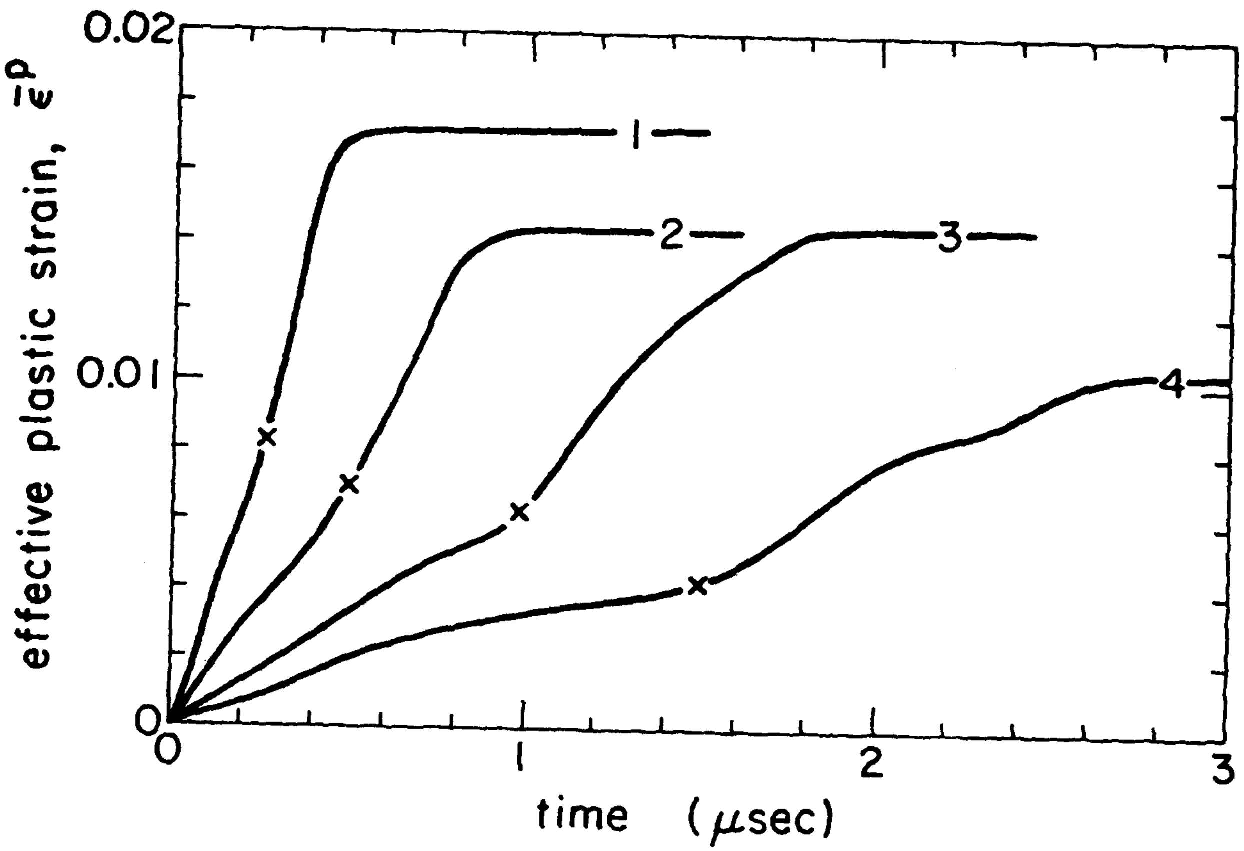

Fig. 4 Effective Plastic Strain as a function of time for plate impact experiment, Sandia data, Ref. 8.

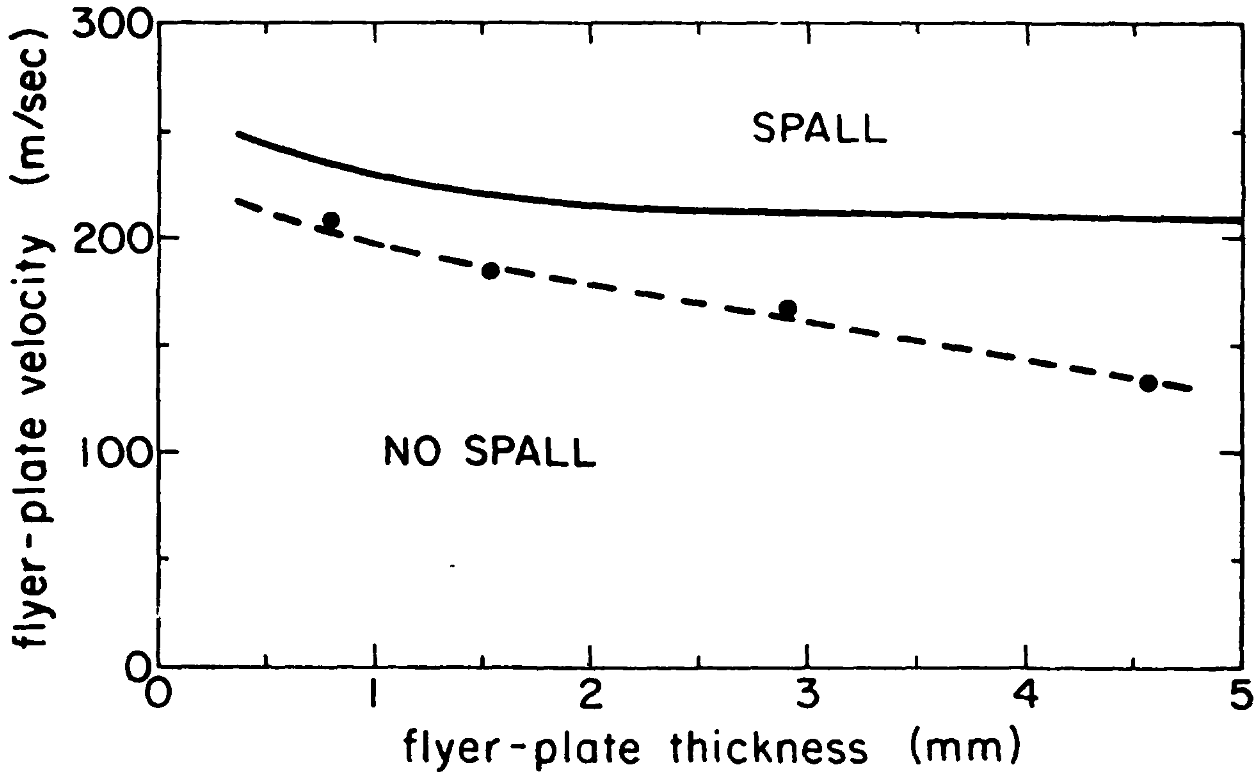

Fig. 5 Comparison of Spall Threshold Theory Prediction
(——— simple void growth;
----- nucleation/void growth model)

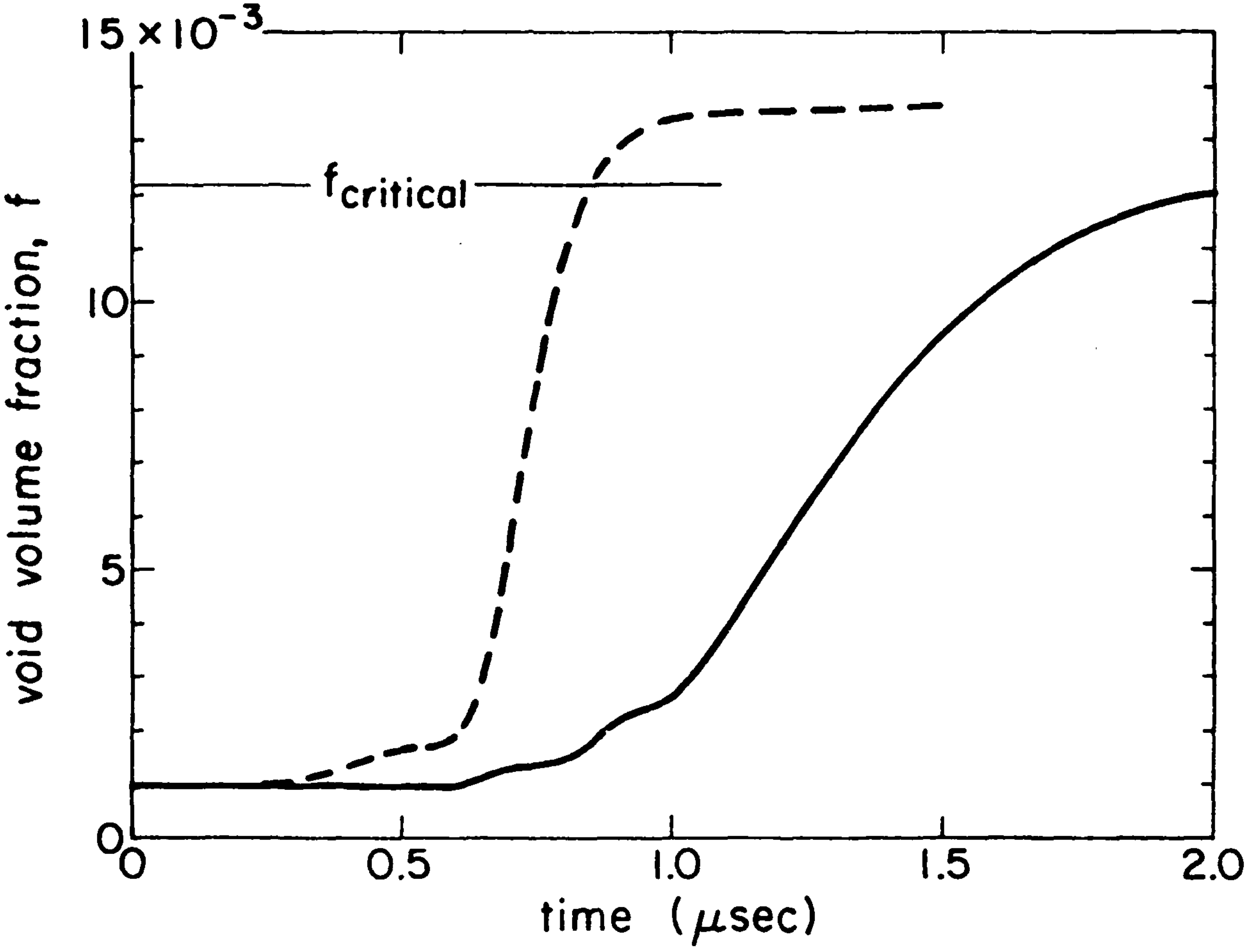

Fig. 6 Maximum void volume fraction in dynamically loaded thick-walled cylinders (——— pulse 1, at spall plane; ----- pulse 2, 0.5 mm from spall plane). Pulse data from Exp. Mechanics, v. 13, No.4, p. 163, 1977.

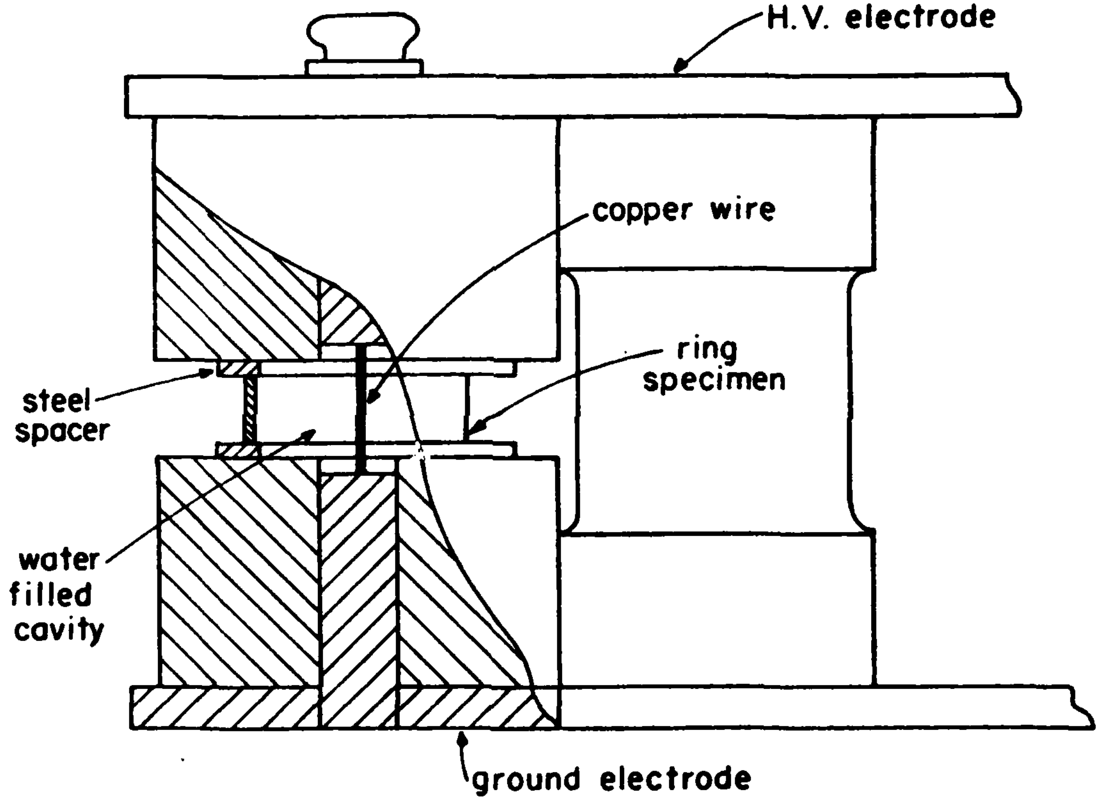

Fig. 7 Exploding-wire Experimental configuration for High Strength Ring Tests.

Participating Scientific Personnel

The following personnel were associated with this project for varying lengths of time during the course of the grant.

Name	Position	Degree Awarded
Dr. I. M. Fyfe	Principal Investigator	----
Dr. J. W. Hancock	Research Associate	----
A. M. Rajendran	Ph.D. Candidate	3/81
K. B. Lim	M..S. Candidate	----

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